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EFFECT OF RESIDUAL STRESSES IN FLOAT-GLASS ON CUTTING QUALITY

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The main reasons for the appearance of rejects during glass cutting are presented: off-cut breakage and breakage during cutting. Attention is focused mainly on the residual stresses in the glass; equipment-related reasons for rejects are briefly discussed. The existing method of monitoring the residual stresses in glass and its drawbacks are examined. These studies have made it possible to clarify the reasons for problems arising during glass cutting. Explanations are given for the results obtained.

Key words: float-glass, mechanical roller cutting, problems during cutting, residual stresses, off-cut breakage, glass breakage during cutting.

The overwhelming majority of sheet-glass workers still use the mechanical roller method of cutting. Glass cutting is done in two stages: first the glass is scored using a roller, i.e., a scratch (groove) with a network of microcracks beneath is made (ordinarily from edge-to-edge of the sheet glass in the case of a rectilinear cut), after which a bending force is applied perpendicular to the sheet plane (the sheet is made to break). This method is based on the property of brittle bodies under tension to break along the weakest section when bent. However, in some cases breaking occurs in an arbitrary direction, resulting in rejection of the sheet.

The reasons for this phenomenon have still not been fully studied. In general, sheet-glass workers believe that the residual stresses in an incorrectly broken sheet are too high (the expression "overtempered glass" is very popular). The standard answer given to this question by glass manufacturers is that the residual stresses in the glass supplied to the sheet-glass workers (as measured at the glass plant's technical control division) correspond to the norm and the probable cause is improperly adjusted equipment.

The present article examines the principal forms of stress arising during float-glass manufacture, the methods used to determine them, and the experimental study of their effect on cutting quality.

The reasons that complications arise during the cutting of float-glass can indeed lie with the cutting equipment and within the glass itself. As concerns the equipment, here the main point is that the manufacturer's recommendations must be followed strictly. Optimal parameters do exist (cutting angle of the roller, pressure and cutting speed); they are determined experimentally for each thickness of the glass. The principles for choosing the parameters are examined in detail in [1 – 4]. The mechanism of roller cutting and the effect of the parameters are studied in [5, 6]. Cutter rollers (and much less often their holder) wear out. Once a definite service life has been exhausted the rollers become blunt and do not cut the glass adequately. As a result a break occurs not along the cut but rather in an arbitrary direction (Fig. 1).

In practice this is precisely the most common reason for rejection to occur during cutting of sheet glass. The recommendations are simple — it is necessary to use the "proper" equipment and the "proper" adjustments and the rollers must be replaced in a timely fashion. In the present article we shall examine in detail the second reason that off-cut breaks occur — the residual stresses in the float-glass and their distribution over a sheet.

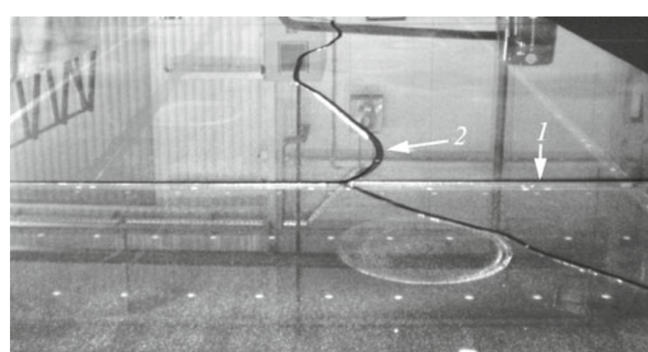

Fig. 1. Off-cut break: *1*) main crack; *2*) additional, undesirable crack.

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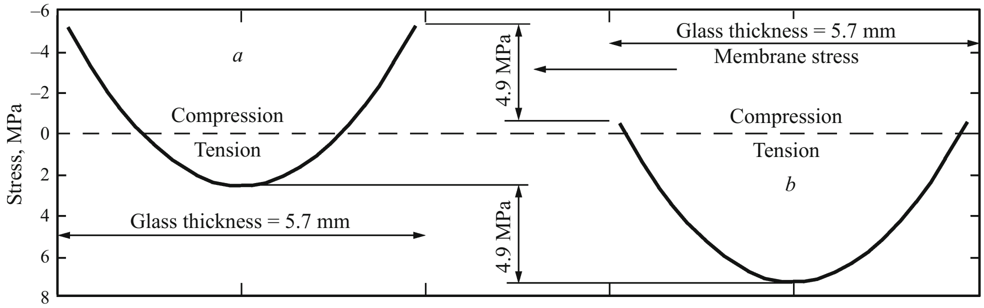

Fig. 2. Stress distribution over the thickness of a float-ribbon: *a*) uniform cooling; *b*) nonuniform cooling.

Formation of Residual Stresses in Float-Glass

Residual stresses appear in glass as it cools, during a transition from the viscoplastic state into the solid state. Because the thermal conductivity of glass is low temperature gradients form over its thickness. The outer layers cool and solidify first. The hotter inner layers cannot compress freely as they cool, because they are coupled to the outer layers which have already cooled. As a result, tensile stresses arise in the inner layers, while compressive stresses arise in the outer layers under the action of the compressed inner layers.

For uniform symmetric cooling the residual stresses are distributed symmetrically and parabolically in the glass relative to the median plane and they are directly proportional to the rate of cooling [7].

The stress distribution in float-glass is complex, since the nonuniformity of cooling in different planes comes into play. As an example we present the stress distribution over the thickness of the glass at a definite point in the central part of a sheet of float-glass. Figure 2 shows the stress distribution at an arbitrary point on the surface of the glass. When the entire surface of the glass cools practically uniformly at the rate 1.12 K/sec the stresses (curve *a*) are symmetric relative to the central axis, and their resultant, called the membrane stress, is zero. If cooling is nonuniform over the thickness of the glass, additional tensile stresses appear at a given point (curve *b*). The profile of the stress distribution is the same but the additional membrane stress shifts the entire pattern in the direction of tension by 4.9 MPa.

Membrane stresses are very likely to appear in a float-ribbon because it is large.

Of course, when a float-ribbon undergoes zone cooling a temperature gradient arises along its length, but because of the stability and inertia of the process this gradient does not engender high membrane stresses.

The nonuniformity of cooling over the width of a float-ribbon has the strongest influence on the appearance of membrane stresses. The problem is that the sides where a float-ribbon is drawn are thinner than the rest of the ribbon and cool more rapidly. A compressive stress arises in them. Correspondingly, tensile stresses are formed in the neighboring region. As a result, the membrane stresses have a characteristic “double-hump” distribution over the width of the glass ribbon. The wave gradually decays toward the center.

Added to this is the property of the ribbon edges to cool more rapidly than the center following the classic pattern: compressive stresses predominate at the edges and tensile stresses at the center.

The operator of the cooling apparatus is faced with a complicated problem — to compensate the nonuniformities indicated by adjusting the rate of cooling in different zones.

Methods for Determining Residual Stresses

A detailed description of optical methods of measuring residual stresses in glass is presented in [8].

Two methods are used to monitor stresses in float-glass. They are based on the birefringence effect, and in the literature they are customarily named the Senarmont and Babinet methods (after the developers of the operating principles of polarimeters).

The Senarmont method is used to measure membrane stresses transverse to the draw line of the float-ribbon. The measurements are performed with a definite step along a marked line. The values obtained are used to construct a curve, called the annealing curve.

The Babinet method is used to determine the maximum stress between the surface and the center of the glass. The procedure is described in GOST 3519 *Optical Materials: Methods for Determining Birefringence* [9]. The measurements are performed on small samples with the dimensions 5 × 10 cm.

The bending-deflection method is used to determine the stress difference between the top and bottom surfaces of a float-ribbon. A narrow strip is cut from the float-ribbon (across and along) and placed on two supports. The magnitude of the bending deflection at the center of the strip is measured. Next the ribbon is turned round and the bending deflection is measured again. The compressive stresses at the bottom of the strip (during the measurements) prevent it from sagging and therefore the magnitude of the bending deflection is inversely proportional to the stresses. This method is inaccurate and gives only the relative stress difference between the glass surfaces.

Previously it was believed that the problems arising during cutting of sheet glass are mainly due to the residual stresses between the surfaces of the sheet and its center, whose value should not exceed 5% of the average ultimate strength of the glass. For this reason a series of normative

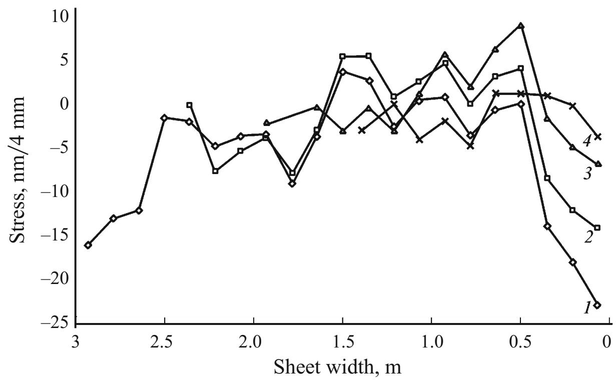

Fig. 3. Variation of the membrane stresses during glass cutting: *1*) starting glass; *2*) glass with 0.5 m cut off; *3*) glass with 1 m cut off; *4*) glass with 1.5 m cut off.

documents regulate the residual stresses over the thickness of the sheet; these stresses are determined by the Babinet method. Specifically, according to paragraph 5.1.4 GOST 111–2001 [10], the magnitude of the residual internal stresses in the glass, which is determined by the path difference between rays in birefringence, should not exceed 70 nm/cm (which for sodium-calcium-silicate glass corresponds to 3 MPa, i.e., approximately 5% of the average ultimate bending strength of float glass).

However, practice shows that in most cases the stresses over the thickness of the float-glass produced by leading manufacturers are 20 – 40 nm/cm, which by no means guarantees that there will be no rejects. No direct and unique correlation is observed between the stresses over the thickness and the problems arising during cutting of sheet glass of large initial size.

On the other hand, practical experience shows that the distribution of the membrane stresses over the thickness of a sheet has a strong influence on the cutting quality. In addition, it is precisely the stresses on the initial (full-format) sheet that play the determining role, because since as the sheet is cut into smaller blanks the stresses in them relax. This is confirmed by, specifically, computer simulation performed with the ANNEAL FLOAT computer program [11].

Stress Relaxation during Cutting of a Glass Sheet

In the course of these studies a series of experiments was conducted in the laboratory at the AGC Float Glass Klin plant on the effect of the cutting of a sheet on the distribution of the membrane stresses. Strips were cut in turn in different directions from the initial format 3210 × 6000 mm sheet and the stresses were measured on the sheet remaining after the strips were cut out.

The measurements were performed in the Stresstter apparatus, designed for measuring the stresses in large-format sheets. The apparatus operates according to the Senarmont principle.

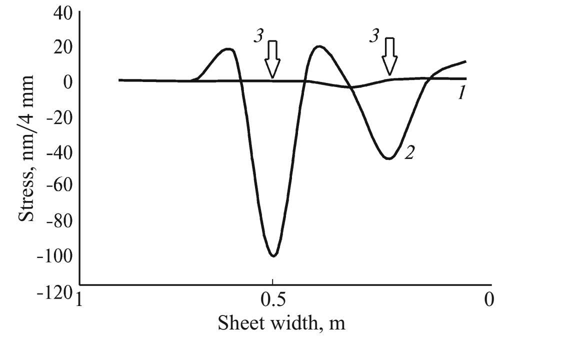

Fig. 4. Annealing curves: *1*) starting sheet; *2*) after heating; *3*) positions of heaters.

The annealing curves for the initial sheet and after several 0.5-m wide strips were successively cut from the sheet are presented in Fig. 3.

According to the plots the membrane-stress distribution curve changes considerably as the dimensions of the sheet decrease. On the whole the stresses decrease.

Together with a change in the membrane stresses the stresses also change over the glass thickness. For this reason measurements on very small samples in a polariscope-polarimeter do not show the pattern in the initial sheet.

Modeling of the Residual Stresses Transverse to the Draw Line

To determine the effect of residual stresses on off-cut breaking of float-glass sheets the stresses were modeled by creating temporary stresses.

Using a flexible heater a strip on the sheet was heated to temperature about 45°C. This creates a temperature gradient in the glass. The heated sections strive to expand, as a result of which compressive stresses arise in them. Annealing curves for a sheet before and after heating are shown in Fig. 4.

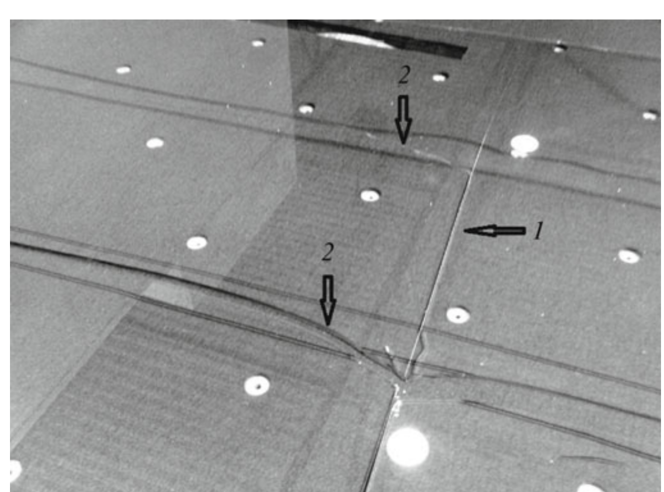

Fig. 5. Off-cut fracture: *1*) main cut; *2*) undesirable off-cut cracks.

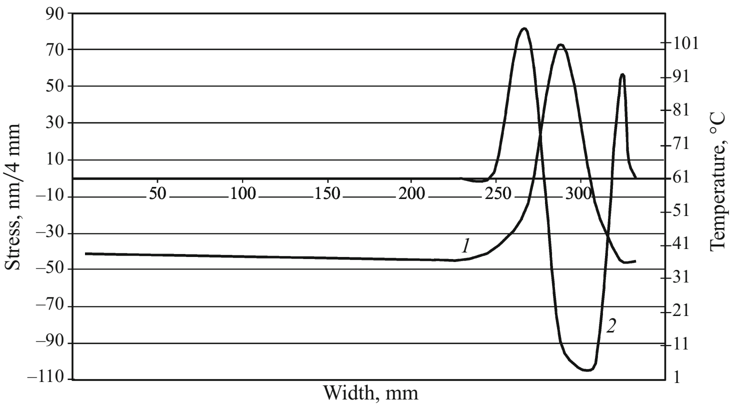

Fig. 6. Stress variation during heating of a sample: *1*) temperature; *2*) stress.

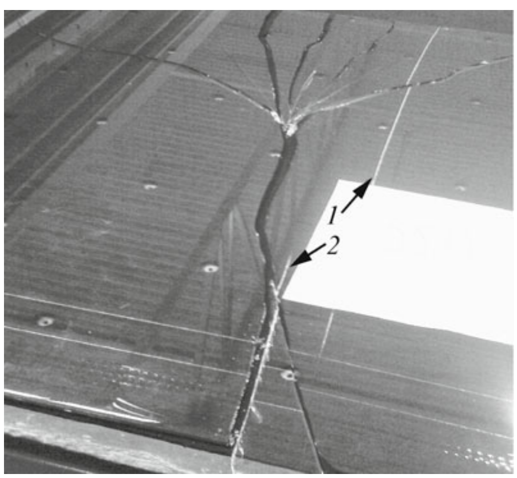

Fig. 7. Reject formed during glass cutting: *1*) cut in the direction away from the maximum stresses (no fracturing); *2*) cut through the zone of maximum stresses (fracturing occurred during the cutting).

Next, the glass was cut. The sheet broke off-cut in the zone where the cut intersected the region of compressive stresses (Fig. 5).

The experiment was repeated several times with different positions of the heater. In all cases the location where the crack propagated away from the line of the cut approximately corresponded to the position of the heater. The explanation of this is as follows. Compressive stresses strengthen the glass [12]. It is known that tempered glass is stronger precisely because of the compressive stresses in the surface layer. A crack reaching the strengthened sections strives to circumvent them and follow the path of least resistance.

Another widely occurring undesirable phenomenon is fracturing of the glass beneath the roller as a scratch is being made. This is probably due to high tensile stresses.

A more powerful infrared heater was used to obtain the tensile stresses. A small region has heated to a temperature close to 100°C. High compressive stressed arose in the heated region, while quite high tensile stresses arose in a neighboring region (Fig. 6).

As the scratch was being made, the glass fractured when the region of tensile stresses was crossed. As the stresses increased (due to intensification of heating) an even more characteristic fracture pattern was observed during cutting (Fig. 7). It should be noted that the break occurred after a nearly immeasurable time elapsed after the roller crossed the future location to which a crack propagated from the line of cut. This is due to the fact that the tensile stresses present in the glass were sufficient for a crack to form from the scratch made and then propagate. Since under such conditions there was not enough time to complete the cut, cracks propagated in arbitrary directions and the stress field in the glass determined their final trajectory.

Since temporary stresses were created in the course of the experiments, actual values of the stress were not presented here. About 30 sec elapsed from heating to stress measurement and then the same time elapsed to cutting. Over this time the temperature equalized somewhat, while the stresses relaxed.

A series of similar experiments with constant stresses and strength calculations, to be performed using specialized computer programs, are being planned to obtain precise values.

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